Fisheries and Oceans Science | Pêches et Océans Sciences

CSAS | SCÉS

Canadian Stock Assessment Secretariat | Secrétariat canadien pour l'évaluation des stocks

Research Document 2000/047 | Document de recherche 2000/047

Not to be cited without permission of the authors [1] | Ne pas citer sans autorisation des auteurs [1]

# Discussion on an Experimental Approach for Northern Abalone Stock Rebuilding in British Columbia

A. Campbell[2], B. Lucas[2], G. Parker[3]

[2]Fisheries and Oceans Canada
Stock Assessment Division, Science Branch
Pacific Biological Station
Nanaimo, B.C.
V9R 5K6

[3]Fisheries and Oceans Canada
Fisheries Management Branch
Pacific Biological Station
Nanaimo, B.C.
V9R 5K6

[1] This series documents the scientific basis for the evaluation of fisheries resources in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

This document is available on the Internet at:

[1] La présente série documente les bases scientifiques des évaluations des ressources halieutiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

Ce document est disponible sur l'Internet à:

http://www.dfo-mpo.gc.ca/csas/

ISSN 1480-4883
Ottawa, 2000

Canada

## 1.0 ABSTRACT

This paper reviews published reports on rebuilding and restocking attempts for abalone stocks. Pilot experiments are proposed that potentially may provide base-line information on large-scale methods to rebuild northern abalone stocks in British Columbia. These include (1) establishing 3 or 4 experimental marine reserves throughout British Columbia to allow experimental manipulation of wild abalone adult densities for increasing abalone recruitment, (2) experimental outplanting of hatchery-reared northern abalone juveniles, on a small scale, to determine optimal size and density for release and probability of success in increasing juvenile and adult abalone densities. An ecosystem approach is recommended in which habitat parameters, algae and invertebrates are monitored. Manipulation of red sea urchins abundance to determine the effects on abalone survival and growth is suggested. Maintaining the northern abalone fishery closure indefinitely and continued large scale index site surveys every 4-5 years to monitor long-term trends in northern abalone populations are also important. Enforcement for the prevention of poaching northern abalone and partnerships between local communities and government agencies will be critical to the success of any rehabilitation attempts and long-term experiments.

## 1.1 RÉSUMÉ

Ce document fait état d'un examen des rapports publiés sur les tentatives de rétablissement et de repeuplement des stocks d'ormeaux. On se propose d'effectuer des projets pilotes qui pourraient fournir des renseignements de base sur les méthodes à grande échelle de rétablissement des stocks d'ormeaux nordiques en Colombie-Britannique. Ces projets comprennent 1) l'instauration de trois ou quatre réserves marines expérimentales, à la grandeur de la Colombie-Britannique, pour la manipulation expérimentale des densités d'ormeaux sauvages adultes, en vue d'accroître le recrutement d'ormeaux, 2) la dispersion en mer expérimentale d'ormeaux nordiques juvéniles d'élevage, à petite échelle, afin de déterminer la taille et la densité optimales pour la dissémination, et d'évaluer les possibilités de réussite de l'augmentation des densités d'ormeaux juvéniles et adultes. On recommande une approche écosystémique avec observation des paramètres de l'habitat, des algues et des invertébrés. On suggère de manipuler l'abondance des oursins rouges dans le but d'évaluer les répercussions sur la survie et la croissance des ormeaux. Il est aussi important de maintenir la fermeture de la pêche de l'ormeau nordique pour une durée indéterminée et de faire, une fois tous les quatre ou cinq ans, une étude à grande échelle des sites indicateurs qui permet de surveiller les tendances à long terme dans les populations d'ormeaux nordiques. L'application de mesures empêchant le braconnage de ce mollusque, et les partenariats entre les collectivités locales et les organismes gouvernementaux, sont d'une importance capitale pour la réussite de toute tentative de restauration et expérience à long terme.

## 2.0 INTRODUCTION

The "northern" or "pinto" abalone, *Haliotis kamtschatkana*, found from Sitka Island, Alaska to Baja California, generally occurs in patchy distribution on exposed and semi-exposed marine coasts. In British Columbia (B.C.), the northern abalone, a traditional food of First Nations, was a target of recreational divers and a modest commercial dive fishery until 1990 when all fisheries were closed due to major stock declines and conservation concerns. The purpose of the coastwide closure was to allow depleted northern abalone populations to rebuild. Stock assessment surveys of selected index sites along the B.C. coast during the fishery closure in the 1990s have shown no evidence of natural stock rebuilding; and in some areas showed further population declines of northern abalone (Campbell 2000b). The lack of recovery of northern abalone populations in B.C., nine years after the abalone fishery closure in 1990, prompted the Committee on the Status of Wildlife in Canada (COSEWIC) to designate the northern abalone as a "threatened" species on April 23, 1999. In addition, Fisheries and Oceans Canada (DFO) hosted a workshop seeking advice (from local communities, First Nations, international research institutes and government organisations) to develop a rebuilding strategy for northern abalone stock in B.C. (Campbell 2000a). Gardner et al. (2000) provided a summary of the overall rebuilding strategy proposed at the workshop for northen abalone stocks along the coast of B.C. The purpose of the present paper is to provide a scientific framework for experimental work to examine potential methods to rehabilitate northern abalone in B.C. This paper should be considered as an integral part of an overall recovery plan for northern abalone in B.C. being developed by DFO. Other important aspects of the recovery plan will include education and enforcement issues to reduce poaching, and developing partnerships between community groups and DFO to encourage local stewardship of the abalone resource and implement some of the experiments suggested in the present paper.

There is a long history of enhancement restocking attempts in marine fish (e.g., salmon) and invertebrates (e.g., lobster) that are questionable in terms of whether the benefits outweigh the costs (Hilborn 1998). Seki and Sano (1998) concluded that long-term large-scale restocking attempts with juvenile abalone (*H. discus hannai*) seed had not enhanced wild stocks in Japan. Tegner (2000) advocated improved fishery management and transplanting of wild adult abalone as being more cost effective for declining abalone stocks than enhancement with hatchery reared larval or juvenile abalone seed in California. Despite pessimism in the success and economic viability of restocking methods, a number of authors advocate a more carefully considered approach that includes an understanding of the biological, ecological and genetic requirements of wild stock, ecosystem complexities, and mortality processes that may optimise survival and growth in restocking attempts (e.g., Blankenship and Leber 1995; Stoner and Glazer 1998; Seki and Taniguchi 2000; Shepherd et al. 2000).

The objective of "rehabilitation", "rebuilding" or "enhancement" of northern abalone stocks is to use a combination of methods to increase the depleted population size to a higher level of abundance and to increase population distribution by replacement of individuals in areas totally depleted of abalone patches. The rebuilding methods to increase abalone abundance would include (1) Fisheries management regulations such as long term fishery closure and enforcement to reduce illegal fishing or eliminate human exploitation of the resource, (2) Stocking or out planting of hatchery-reared larvae and

or juveniles into the wild, (3) Experimental adaptive management which includes manipulating concentrations of wild abalone and or other competitive and predator species at different sites. There probably is sufficient pristine habitat throughout much of the B.C. coast that is suitable for northern abalone that we do not consider large scale habitat restoration is required as a rebuilding tool in this paper.

In developing these rebuilding methods consideration of the following will be required: (1) genetic and disease management, (2) an ecosystem approach (Perry 1999) which uses measurement criteria that are simple and efficient under field conditions, (3) some of the methodology testing should be conducted in parallel or simultaneously, (4) outline new research needs and development of innovative techniques to help the general methods, (5) development of feedback mechanisms and criteria of success to allow regular evaluation, (6) Clearly there is a need to have a moderate research framework to allow new ideas and experimental results to be regularly considered, evaluated and incorporated into management of the rehabilitation process. Much of the framework proposed in this paper advocates for experimental pilot projects that allows for the evaluation of methods prior to undergoing, for example, large-scale restocking enhancement.

## 3.0 GENERAL BIOLOGY

Since the biology and ecology of *H. kamtschatkana* was comprehensively reviewed by Sloan and Breen (1988) and Campbell (1997), only a summary of the relevant biology is presented in this section. Occurring in a wide variety of habitats from intertidal to 100m depths, most adults are found <10 m on top of rocky substrates exposed in areas of moderate to high water movement. Mature males and adults are external spawners broadcasting their gametes synchronously in shallow subtidal areas during summer (Breen and Adkins 1980). Fertilisation success depends on the aggregation density of abalone (Clavier 1992; McShane 1995a,b; Babcock and Keesing 1999). Fertilised eggs hatch into planktonic larvae (of 5-10 day duration) that can be dispersed by local water currents. Larval exchange in some abalone species may occur in small geographic areas (on a scale of hundreds of meters to several kilometres) (McShane 1995a). Because of their cryptic nature, practically nothing is known about the early juvenile stages (1 - 3 years) of the northern abalone in B.C. and requires further study (Sloan and Breen 1988). Estimated age at which northern abalone reach maturity (about 55 mm shell length, SL) is between 2 to 5 years and the fishery recruit size of 100 mm SL is between 6 to 8 years in B.C. depending on local abiotic and biotic factors (Quayle 1971; Sloan and Breen 1988). "Surf" abalone at highly exposed sites in B.C. may never reach the recruit size of 100 mm SL (Sloan and Breen 1988). Abalone are herbivorous and as juveniles develop to maturity their diet changes from benthic diatoms and microalgae to macroalgae (Sloan and Breen 1988). Recruitment of larvae and juveniles to the adult stage is usually low and sporadic. Little is known about the process of recruitment for northern abalone in B.C. (Campbell 2000b). A large number of factors can influence the quantity and location of abalone recruitment (e.g., fertilization success influenced by adult spawning aggregation densities, local hydrodynamics and storms may entrain or widely disperse larvae during their short larval period prior to settlement, and local mortality and growth rates may differentially act on juvenile and adult abalone survival) (McShane 1995a,b; Roberts et al. 1999). The relatively long adult period (probably between 5 and 30 years) may help sustain the species during periods of low recruitment. However, the frequency and size of patches of northern abalone required to maintain sufficient

recruitment for a healthy population requires investigation.

Natural mortality may be caused by environmental factors (storms, episodic high temperature, low salinity), predators (e.g., sea otter, *Enhydra lutris*; crab, *Cancer productus*; sea stars, *Pycnopodia helianthoides*; and octopus, *Octopus dofleini*), starvation (lack of algae), competitors (e.g., red sea urchins, *Strongylocentrotus franciscanus*) for space and food, parasites and disease (Sloan and Breen 1988; Shepherd and Breen 1992; Bower 2000). Population expansion of the sea otter, a major predator of *H. kamtschatkana* in B.C. (Watson 2000), in addition to human exploitation, poses a serious potential threat to future northern abalone populations.

## 4.0 REBUILDING EXPERIMENTS

Tables 1 and 2 provide a list of the potential general experiments and timelines required. The following sections provide a framework for each of the general rebuilding experimental categories, brief reviews of recent published papers on appropriate experiments, pros and cons, and emphasis on experiments that we believe are likely to have the most benefit.

### 4.1 Fishery Closure, Enforcement and Partnerships

Long term closure of the abalone fishery to all users is an important management tool in attempting to reduce human exploitation and halting the decline and in rehabilitation of northern abalone populations in B. C. Continuing the index site surveys of abalone populations in large areas of B. C. is mandatory in monitoring general abalone stock trends (Campbell 2000b).

Prevention of illegal harvesting of abalone during the closure is a serious problem and is one of the highest priorities in the overall rebuilding plan (Gardner et al. 2000). Actions to prevent poaching include ensuring enforcement coverage throughout B. C. using government fishery officers and First Nations fishery "guardian" personnel, providing genetic tools to identify illegally caught northern abalone, and educating the public and communities.

Partnerships between local communities and government agencies will be important in executing the field experiments proposed in this paper and will encourage local stewardship of the abalone resource. Traditional ecological knowledge and wisdom of First Nations (Turner et al. 2000) may be valuable when integrated with management and scientific methods for rehabilitating northern abalone.

### 4.2 Restocking

#### 4.2.1 *Larval Seeding*

Abalone larvae can potentially be used to enhance or restore local populations. This provides a way to augment natural larval settlement, allowing the larvae that settle and metamorphose to grow and develop into mature abalone in the wild.

Releasing hatchery reared abalone larvae has met with limited success, with most studies concluding that larval release is not suitable for large scale restocking (Roberts et al. 1999). Competent paua (*H. iris*) larvae were released from buckets over a 1 $m^2$ area in subtidal gullies in New Zealand in 1985 (Tong et al. 1987). Although some larvae dispersed outside the 1 $m^2$ area, increased densities of late post larvae and early juveniles were found within the 1 $m^2$ area 3 months later compared to control

areas 5 and 18 m distant (Tong et al. 1987). During 1986, when tents (each covering 1 $m^2$) were used to retain larvae for 24 hr after release, only 10% of the released larvae settled successfully. After 4 – 5 months the densities surviving were not sufficient to justify the increased costs and detailed field work required for seeding larvae compared to juvenile seeding (Schiel 1992). Schiel (1992) also concluded that this experimental method would be difficult to use on a large scale.

Abalone larvae were released in California (McCormick et al. 1994) and in Mexico sporadically (Ortiz-Quintanilla 1980), but the results were not evaluated.

Blacklip (*H. rubra*) and greenlip (*H. laevigata*) larvae were released at varying densities over replicate 500 $m^2$ areas in South Australia during 1994 and 1995 (Preece et al. 1997, Shepherd et al. 2000). Blacklip densities 19 days post release were highest from intermediate larval density releases (1600, 16000, and 80000/$m^2$). Greenlip densities 6 days post release were three times higher at larval density releases of 120000/$m^2$ than those at 2000/$m^2$. After 49 days, the mean juvenile abalone density overall was 3.8/$m^2$ and after 11 months was only 0.6/$m^2$. For these experiments, survival 6 – 9 days after settlement was 0.02 – 7.8%, in the next 4 – 6 weeks M (mean natural mortality rate) was 1.8 – 2.8/month and in the 11 months after that mean M was 2.9 (SE 0.3)/year. Due to the density-dependent mortality of the larval stage Preece et al (1997) recommended future seeding be tested at even lower release densities, and estimated that only 74 individual greenlip abalone would survive to 6 years from each million larvae seeded. Shepherd et al. (2000) did not recommend larval seeding as a restocking method in South Australia, because of the strongly density dependent mortality of the larval stage. Roberts et al. (1999) concluded that larval seeding trials in New Zealand and Australia did not produce adequate cost-effective enhancement.

#### **4.2.1.1** *Potential Methods*

Broodstock are usually conditioned and spawned in a hatchery, but wild abalone found in good spawning condition could be spawned on site and the fertilised eggs released into the wild. In the hatchery, sperm and eggs are mixed at optimal relative densities for fertilisation. After a few hours, the fertilised eggs are drawn off and developing larvae are held for several days until they are competent to settle (McCormick 2000). In the wild, the planktonic larval phase for northern abalone is 4-8 days at 14-10°C (Sloan and Breen 1988). Before settlement, the larvae must be transported to a site with suitable micro-habitat for small abalone (Rudd 1995) that is near suitable habitat for larger juveniles and adults. Small juvenile abalone < 10 mm SL are generally found in water 5 – 15 m deep on rock or boulder substrates that are bare or covered with encrusting corraline red algae (Sloan and Breen 1988). Larger juveniles 10 – 70 mm SL have a tendency for cryptic habitats, but adults tend to be more common on exposed rock and boulders (Sloan and Breen 1988).

#### **4.2.1.2** *Pros and Cons*

Advantages: inexpensive, minimal hatchery facilities required since no ongoing husbandry required for larval and juvenile grow out, juveniles grown in the wild from seeded larvae may have more natural behaviour and reaction to predators than released hatchery-reared juveniles.

Disadvantages: high mortality, difficult to distinguish seeded from wild larvae (means to distinguish planted from wild larvae required by using distinctive phenotypic markers such as shell colour or shape to determine survival (McCormick et al. 1994)), biological and economic assessment difficult, time-consuming to analyse samples of larvae collected.

### 4.2.2 *Juvenile Seeding*

Hatchery reared juvenile abalone can be seeded into suitable habitats to increase local densities and survivors may eventually contribute to the reproductive output of abalone meta-populations in the area.

Restoring abalone populations through seeding with hatchery-reared juvenile abalone has produced mixed results. Survival of seeded juveniles depends on abalone size, condition and origin (wild or hatchery-reared), predator abundance, method of planting, substrate type, and food availability (McCormick et al. 1994, Shepherd et al. 2000). Most studies found that survival of seeded abalone increased with seed size. One year survival rates for *H. gigantea*, *H. sieboldi* and *H. discus* ≥ 40 mm SL were more than 60% (Inoue 1976), survival for Ezo abalone (*H. discus hannai*) 15 mm SL was 17% and 21 mm SL was 33% (Momma et al. 1980) in Japan. After 491 days, Miyamoto et al. (1982) found < 10% survival for Ezo abalone < 10 mm SL and 23 – 31% for seed > 22 mm SL. In contrast, for the 2.8% of red (*H. rufescens*) and green (*H. fulgens*) abalone that were recovered in six large-scale experiments in southern California, there was no evidence that survival increased over the 10 mm – 80 mm SL size range that was seeded (Tegner and Butler 1989). Likewise, when 15 – 19 mm SL red abalone were seeded using concrete block structures, the estimated survival was 32% after 1 year and 24% after 2 years, beyond that time there was no evidence of differences in survival due to seed size (Davis 1995).

Seed abalone must be distinguishable from wild abalone to allow evaluation of enhancement experiments. A notched cut in hatchery-raised abalone shells > 25 mm SL can be identified underwater, and the growth from the notched edge measured (Tegner and Butler 1989). Abalone shell colour is influenced by diet colour, therefore manipulating diet in the hatchery can easily mark large numbers of abalone. Feeding young abalone food that is a different colour from the food wild abalone eat produces a colour difference in the early shells. When hatchery-reared abalone are placed in the wild, the change in diet causes a change in shell colour that is easily detectable for at least 1 year (Ebert 1989; Shepherd et al. 2000; Tegner and Butler 1989). Although more time consuming than previous methods, numbered metal or plastic tags can be attached to the shell using marine epoxy or cyanoacrylate adhesive (Shepherd et al. 2000).

Predator removal may increase short-term survival of seeded juveniles. When Tegner and Butler (1985) transplanted reproductively-mature green abalone and removed predators and scavengers, abalone survival increased from 58% to 93%. The authors concluded that predator control would have to be nearly continuous to substantially improve long-term survival. Hatchery-reared abalone are more likely to be consumed by predators, as they have significant differences in behaviour from that of wild abalone (Shepherd et al. 2000, Tegner and Butler 1989). The impact of predators can be reduced if seed abalone are acclimated to the wild before release (Schiel and Weldon 1987). Juvenile greenlip abalone (*H. laevigata*) seeded onto artificial habitats in areas of Tasmania with few natural predators had an annual mortality rate of only 0.18 (Shepherd et al. 2000).

Seeding substrates and modules may provide an effective way to acclimate hatchery-reared juvenile abalone, while significantly reducing the time divers need to spend underwater placing seed. Hand seeding 10,000 juveniles individually on the substrate at densities of 50 – 70/m$^2$ took 4 underwater hours in New Zealand (Schiel 1992). Underwater time can be reduced by first letting seed abalone attach to small substrates, then placing the substrates in appropriate habitat without handling the

individual abalone (Tegner and Butler 1985, 1989). Oyster shell worked well to reduce handling for red abalone < 25 mm SL in California (Tegner and Butler 1985, 1989), abalone shells and bricks were effective for blacklip abalone (*H. rubra*) in Tasmania (Shepherd et al. 2000). A simple mesh and polyethylene pipe planting module has been used to protect seeded juveniles from predators and reduce initial mortality following placement in California (McCormick et al. 1994). A PVC release module was used to hold juvenile abalone for 24 hrs in seeding experiments in South Africa; all the seed had left the module within 48 hrs after opening (Sweijd et al. 1998). A concrete module with a delayed automatic release (Ebert and Ebert 1988) was effective in protecting juvenile hatchery-reared red abalone for 1 – 2 days after placement (Ebert 1989), but made no difference in survival rates over 2 years from those of abalone hand planted while attached to red algae (Rogers-Bennett and Pearse 1998).

Choice of appropriate habitat for seeding juvenile abalone is critical. Habitat shift was the greatest cause of mortality for 80,000 paua (*H. iris*) seeded in New Zealand in 1990 – 1991 when sand movement buried juvenile habitat. In northern California, recapture rates were not related to adult abalone densities, but were significantly higher at sites with adult urchins (Rogers-Bennett and Pearse 1998).

The contribution that seeded juveniles may make to future recruitment has not yet been fully evaluated. Whereas extensive restocking of juvenile abalone in Japan has contributed to the commercial harvest, restocking has not enhanced natural stocks (Seki and Taniguchi 2000; Seki and Sano 1998). Gaffney et al. (1996) reported that offspring of the 42,431 red abalone planted in 1979 in southern California dominated the commercial abalone catch in 1992, but these results were questioned and could be an artefact (Tegner 2000; Burton and Tegner 2000). Three of the red abalone released at 45 mm SL in California had bulky, ripe gonads a year later and therefore were probably capable of spawning and contributing to local repopulation (Ebert 1989). Although long term effects have not been reported, seeded abalone may contribute to long-term restocking through egg production in overfished areas (Shepherd et al. 2000)

Roberts et al. (1999) found that large scale experiments indicated that some juvenile reseeding trials could be cost effective and depended on survival rates and abalone market prices (e.g., Schiel 1993). However, most economic assessments found that juvenile seeding were not cost effective (McCormick 2000; Seki and Sano 1998). Shepherd et al. (2000) suggested that there was some scope for juvenile enhancement in marine farming operations.

The main objective of restocking programmes in British Columbia is not economic gain, but restoring wild abalone populations to self-sustaining levels. The availability of juvenile abalone from aquaculture pilot projects would help to make this method of rehabilitation an appealing option. Despite the considerable expense and time required to seed juvenile abalone, and the possibly low survival rates, juvenile seeding may provide an effective method to replenish brood stock that can eventually repopulate some local areas.

#### **4.2.2.1** *Potential Methods*

The first step in testing juvenile seeding as a method to restore abalone populations is to select an appropriate area that is near the source of the parent brood stock of the juveniles that will be used in the experiment. Using offspring of local brood stock is important for maintaining natural genetic diversity and for minimising the transport of disease and other pathogens among coastal areas. We will be limited to areas near where brood stock are obtained for use in juvenile seed production by

aquaculture facilities; at present these are projected to include Kitkatla on the north coast, Denman Island on the east coast of Vancouver Island, and the Barnfield region on the west coast of Vancouver Island. Juveniles from other areas may become available as the abalone rehabilitation and aquaculture programmes develop.

Experimental sites will be chosen within the selected areas based on certain characteristics, such as carrying capacity, of potential sites. Juvenile abalone have specific habitat and food requirements, as mentioned above, depending on the size being seeded. Adequate food, rock substrates, currents and few competitors must be present in selected experimental sites. In addition, the sites should have a history of abalone presence. Suitable sites should have natural barriers to immigration and emigration of juvenile and adult abalone to isolate the benthic stage in the experimental treatments from one another. Preliminary surveys are required to collect habitat data to determine suitable experimental sites. Timed swims and transects surveys could be used in the potential experimental areas to collect information on substrate type, exposure, slope, depth, salinity, surface temperature, temperature at maximum depth, number of abalone, size frequency of abalone, algal species abundance, urchin abundance, and sea star (e.g., *Pycnopodia*) abundance. The historical abalone abundance and densities from published reports, past surveys, local expertise, abalone fishers and fishing logs will be used along with the habitat survey data to select experimental sites. Once the habitat survey results are reported and the experimental design is finalised, sites will be selected that are appropriate for the experiment being conducted. The experimental sites should be permanently marked underwater, with supporting underwater video footage and surface reference photographs . After marking, the sites will be comprehensively surveyed non-destructively to assess stocks and provide baseline ecosystem data (including relative abundance indices of algal and invertebrate species).

If enough suitable sites are available in areas appropriate for seeding juvenile abalone from the aquaculture pilot projects, we recommend a factorial experiment to determine the best size and density of juveniles for maximum survival. Two sizes of juveniles could be seeded at 2 different seeding densities, along with 2 controls (one site that remains undisturbed and one possible procedural control where experimental procedures are conducted at the site by adding seeding containers but with no abalone seed). A total of 6 treatments, 4 replicates per treatment could be randomly assigned to each of a total 24 sites. This experiment could also be repeated in a second and third area, if logistics allow and juvenile seed are available. Tagged abalone of each combination of size and density would be seeded at the selected plots within each area. An additional treatment to determine the effects of sea urchin presence on juvenile abalone survival could be conducted if additional sites are available with and without sea urchins, or by removing all urchins from some experimental sites (e.g., see Table 3 for general experimental design). The large number of treatments will require that each replicate site be small (<1 ha, e.g., 20m x 20m) so that sampling and monitoring can be logistically efficient. The sites would have to be at least 50m apart, with a natural barrier, so that there is no exchange of abalone between sites.

The most effective and efficient method of seeding will be determined in advance through small-scale experiments. Several small substrates and modules will be tested and monitored daily for one week and weekly thereafter for 1 month to compare the time required and the survival for each method.

The seeding experiments should be monitored by conducting surveys 1 month after seeding, every 3 months for the first year, and once yearly thereafter for at least 5 years. Site monitoring will include dive surveys to assess abalone survival and density, and critical ecosystem components as

determined from habitat and stock assessment surveys of the sites. Local community groups will be responsible for much of the monitoring, but DFO dive teams should assist initially to train competent local individuals and to fine tune the monitoring and thereafter as required. After initial experimental results are available, the experiments will be assessed for compliance with the objectives and may be modified accordingly.

#### 4.2.2.2 *Pros and Cons*

There are several advantages of juvenile seeding for rebuilding abalone stocks. The costs are moderate because juveniles will be available from aquaculture projects. The seeded juveniles will have wild food resources available to them, so no active culturing to the adult phase is required.

The disadvantages of juvenile seeding include the time consuming monitoring required to assess the results. The experimental areas will be restricted to areas where local hatchery-reared juvenile stock is available. Mortality of hatchery grown juveniles may be high for many reasons, including inadequate predator response behaviour (Schiel & Weldon 1987).

### 4.3 Experimental Adaptive Management

Fishery closure in different sized marine reserves (i.e., eliminate poaching), controlled experimental fishing of specific species (e.g., abalone, predators or competitors) and transplanting wild abalone are some tools that can be used to experimentally test methods for rehabilitation. Below, we review published methods and propose some appropriate experimental approaches.

#### 4.3.1 *Abalone transplant manipulation*

Emmett and Jamieson (1988) transplanted sublegal northern abalone from exposed sites supporting poor growth to more productive areas in Barkley Sound, B. C., to determine biological and economic feasibility. Several sites showed a reasonable rate of return of legal-sized abalone 2 years after transplant. The study did not evaluate the method to potentially enhance reproductive output or recruitment in the transplant areas. Tegner (1992, 1993, 2000) reported on transplanting reproductively mature green abalone in California which subsequently showed strong evidence of successful local recruitment until the brood stock were poached. The long-term success of the brood stock transplant was dependent on adult survival and density for fertilisation success and local hydrodynamics for larval settlement (Babcock and Keesing 1999).

#### 4.3.2 *Predator & competitor evaluation*

Sea urchins are often dominant herbivores having a major influence on algal communities in shallow subtidal marine areas. In some Australian locations, there was a negative association detected between density of sea urchins and abalone, although the interactive mechanisms were unknown (Andrew and Underwood 1992; Andrew et al. 1998). In other countries, abalone seemed to benefit from the presence of sea urchins (Tegner and Levin 1982; Mayfield et al. 1997; Kiyomoto and Yamasaki 1997; Rogers-Bennett and Pearse 1998). The spine canopy of red sea urchins, in fishery protected sites, was considered to provide increased survival for young juvenile abalone compared to heavily fished areas with low numbers of urchins in California (Rogers-Bennett and Pearse 1998, in press). However, considerable more research is required to understand the mechanisms of urchin-

abalone interactions and the effect of predators. Little is known about predators (e.g., sea otter, *Enhydra lutris*; crab, *Cancer productus*; sea stars, *Pycnopodia helianthoides*; and octopus, *Octopus dofleini*) affecting long term abalone populations in B.C. (Sloan and Breen 1988). The expansion sea otter populations, a major predator of *H. kamtschatkana* in B.C. (Watson 2000), poses a serious threat to future northern abalone populations.

In B.C., no studies have been conducted to determine the effect of red sea urchin densities on northern abalone abundance, survival and growth. We speculate that there may be optimum densities of red sea urchins that provide spine canopy protection for optimal survival and growth to both urchins and abalone progeny. Areas in B.C. with high red sea urchin densities and or long-term no-take MPAs or marine reserves may be counter productive because high densities of red sea urchins may inhibit abalone and urchin recruitment through competition for food and low growth and survival. Non fished areas typically produce populations of large sized older individuals. The assumption that large animals produce high numbers of viable gametes needs to be tested to determine at what (1) size or age adult abalone may be become senescent, or (2) densities (high and low) reduce reproductive efficiency and total fertilised viable gamete yield. Occasional low level removal of red sea urchins from locations of high density may be beneficial in terms of reducing competition for food.

#### 4.3.3 *Scientific reserves and or Marine Protected Areas*

The need for marine protected areas (mpas) and marine refugia or reserves as a means to preserve biodiversity, protect and or enhance specific commercial species abundance has been advocated by many, but there are few published studies on their benefits to abalone (e.g., Dugan and Davis 1993; Shepherd and Brown 1993; Tegner 1993, 2000; Edgar and Barrett 1999; Davis 2000; Jamieson 2000; Jamieson and Lessard 2000; Jamieson and Levings 2000). Tegner (1992, 1993) reported on transplanting adult green abalone (*H. fulgens*) in a closed area in southern California with some initial success in local recruitment before the brood stock was removed by poaching. Wallace (1999) reported a dense northern abalone (*H. kamtschatkana*) population with mostly large and mature individuals in a closed area adjacent to William's Head Penitentiary, Victoria, B.C.; however, beyond the patrolled area, densities and average sizes were reduced, probably due to poaching. Rogers-Bennett and Pearse (1998, in press), showed the indirect benefits of marine reserves: in areas closed to fishing, juvenile abalone (*H. rufescens* and *H. walallensis*) had increased survival under the red sea urchin canopy, which acted as protection from predators, compared to fished areas where red sea urchins densities had declined. Edgar and Barrett (1999) showed that Tasmanian marine reserves over a 6-year period had substantially different ecosystems from those ecosystems that were fished. They showed increases in abalone (*H. rubra*) densities in a reserve compared to fished areas, and that densities of small abalone decreased and those of large abalone increased in four Tasmanian reserves.

Clearly the use of marine reserves to protect ecosystems and abalone as a management tool is in its infancy. Refuge design to effectively assist northern abalone must consider the population biology, the local oceanographic regime, distances or spatial scales of brood stock sources and subsequent recruitment and feasibility of monitoring populations and enforcement (Tegner 1993; Campbell 2000; Jamieson 2000; Rogers-Bennett et al. 2000). Roberts (1998) argued that, instead of determining the location of "sources" (areas with reproductive stock that contribute major quantities of progeny recruits) and how dispersal and recruitment occurs to "sinks" (areas receiving recruits but producing few progeny) of a species, which may be extremely difficult, establishing a dense network of marine

reserves in a wide variety of habitats and locations would be a way of overcoming the problem. Areas with present or a past history of high abalone densities and recruitment could be easily identified as "source" areas, but identification of "sink" areas would be difficult. There is little practical experience as to the appropriate size of marine reserves for northern abalone, how to enforce restrictions and what activities should be permitted within the reserve, and providing realistic scientific objectives to test. At present the whole of B.C. is closed to fishing of northern abalone. Having many marine reserves may be as difficult to enforce as the complete fishery closure throughout B.C.

Garcia-Charton and Perez-Ruzafa (1999) noted that attempting to evaluate the success of marine reserves can be difficult because of the spatial and temporal heterogeneity of ecosystems. They argue that evaluation of the "reserve effect" can be confounded by some aspects of the "habitat effect". Detection of the effects of protection will depend on the choice of adequate spatial and temporal scales. The habitat scale and species involved are important when designing field experiments aiming to measure reserve effects. Many replicate protected areas should be compared with the same number of control or non-protected areas, before and after protection (Underwood 1997). Different sizes of reserves need to be tested and the study duration must be long term (>10 years) to distinguish between long term trends and short term variability (Menge 1997).

Jamieson and Levings (2000) advocated that, although population reference points for single-species fishery management are established for some species, much study is required to establish comparable ecosystem reference points for the management and overall sustainability of ecosystems and fisheries.

#### 4.3.4 *Experimental Methods*

We believe that experimental management should be attempted by establishing a series of experimental marine reserves (closure to all dive fisheries by scientific permit) of different sizes replicated in 2-4 different areas along the B.C. coast that have different contrasting ecosystems, habitats, water current patterns or predator complexes for evaluation [e.g., (1) Queen Charlotte Islands, (2) central/north coast of B.C., (3) west coast of Vancouver Island, and (4) an area with sea otters present]. The size of each area probably should be about 5 - 10 km of straight coastline to provide sufficient area for the replicate study sites. The areas should be closed for at least 10 years to allow the experiments to be monitored. Experiments could include treatments such as (1) controls (no manipulation), (2) abalone removals from some sites, (3) transplanted to nearby sites, (4) sites with red sea urchins present and absent (naturally or based on removals). The experimental development and work should involve local communities and First Nations from inception to help develop the protocols, conduct preliminary surveys to identify potential and establish the experimental sites, survey and monitor the experiments, as well as to enforce fishery closures. Site selection will require evaluating and accounting for the potential invasion of the sea otter, a major predator of *H. kamtschatkana*. The process will involve exploratory surveys, habitat definition and mapping of sites, surveys to estimate invertebrates species and marine algae abundance prior to and after treatments, long term monitoring will also be required.

A specific experiment could involve the removal of red sea urchins in some sites with related treatments to determine the scale of abalone recruitment. The following are the types of questions to be asked:

1. Does removing and or introducing adult abalone change the abundance of abalone recruits?
2. Does removing red sea urchins increase or decrease abalone abundance?

3. What ecosystem changes (especially algal species composition) and accompanying effects on abalone will occur with red sea urchin removal?

The design of a multi-factorial experiment could include two main factors (Table 4):

(1) Abalone. The factor would include three levels (add, remove, and not add/remove including a control). Reproductively mature northern abalone (≥70 mm SL) could be removed from one site and added to another site to determine if the addition of broodstock increases the densities of abalone recruits (<60 mm SL). A number of mechanisms which contribute to recruitment on a small spatial scale could include (a) brood stock adults and larval supply are from the same site and or (b) adults in a site may encourage larvae from other areas to settle and or increase juvenile survival.

(2) Red Sea Urchins. The factor would include two levels (Non removal and removal of urchins). Sites for removal of red sea urchins would have all urchins removed and each year any new urchins should be removed to keep the sites free of urchins.

The experiment is symmetric. Four replicate sites would be needed per treatment combination. This means a total 24 replicate sites will be required. After the initial preparation and monitoring of sites and treatments which may take 2-3 years, sampling and sea urchin removal maintenance should be repeated at least once a year for at least 5 years. If the number of treatments is not logistically possible then they may have to be reduced.

Replicate sites should be of manageable size; about 1-2 ha in size (along a straight coastline, on reefs, or next to islands) separated by at least 100 m and a natural barrier. Depth ranges for sampling at each site would include only areas where most abalone are found (e.g., low intertidal to about 10 m depth datum).

For each replicate site and sample period, sea urchins, abalone, sea stars, crabs (other invertebrates?) should be counted in at least ten 10 x 1 m randomly placed transects. The optimal number and size of transects required to provide reasonable sampling precision and power to detect changes between treatments and over time within treatments should be estimated at several sites prior to finalising the sampling scheme at the beginning of the experiment. The transects could be sampled by divers in a non destructive manner by counting species in 1 $m^2$ quadrats along a 10 m line. Abalone and urchin size could be measured with callipers. The percentage cover of different broad groups of algae, substrate types should also be recorded for each transect. Consideration should also be made in stratifying each site according to several depth groups (which may provide information on different general habitat types) and randomly sampling within each strata. Sampling should be conducted at least once per year, one year before treatment and for at least 5-10 years after treatment to distinguish between short-term variability from long-term trends.

All transplanted abalone adults should be tagged with individual identifying numbers so that survival and growth can be monitored.

Subsidiary work could include adding larval collectors (e.g., Babcock and Keesing 1999) and or juvenile collectors (Davis 1995) in the sites and certain distances from the sites to compare possible contribution of brood stock to larval settlement and juvenile abundance indices between areas. Local current patterns could also be studied using drift bottles during the summer adult abalone spawning period (June-August).

Criteria to determine changes in abalone recruitment should include measuring densities of juvenile abalone (<60 mm SL), (and adults in the long-term) within sites using the transect surveys

(overturning small rocks may be required to observe cryptic individuals), and inside/outside the sites with juvenile collectors.

#### 4.3.5 *Pros and Cons*

The advantages are that experimental marines reserves (1) are reasonably easy to define and implement, (2) provide natural habitats and local abalone (disease-free and genetic) stock to test methods to increase likelihood of successful fertilization and increase recruitment, (3) should be cost efficient to survey and monitor to prevent poaching, (4) provide opportunity to compare different ecosystems and abalone ecological requirements.

The disadvantages are (1) the risk of poaching abalone in curtailing experiment, (2) may be difficult to detect recruitment if larvae are transported large distances from the experimental sites, (3) no control on predators to reduce abalone mortality, and (4) long time period to assess results.

### 4.4 Survey Methods

A number of survey methods have been used to estimate abalone abundance, including timed swims (Shepherd 1985; McShane 1994,1995b), randomly placed quadrats (Schiel 1993), the "Breen" quadrat index method (Breen and Adkins 1979), transects (Andrew and Underwood 1992; Cripps and Campbell 1998), Leslie and Delury regression techniques (Hirayama et al. 1989), and mark-recapture techniques including change-in-ratio method (Nash et al. 1994). Hart et al. (1997a,b) compared several survey techniques (radial transects, catch-effort Leslie method, timed swims, change-in-ratio, mark-recapture Petersen's method) in 2.5 - 5.0 ha plots and concluded that the transect survey method (using 30 $m^2$ as the sample unit) with a stratified random sampling design was the safer and more robust alternative for surveying *H. rubra* stocks in Victoria, Australia. The change-in-ratio and mark-recapture (along with an equal catchability test) methods were also considered efficient but required more intensive data collection. Clearly alternate survey methods may require to be developed for northern abalone and will depend on the objectives and logistics of the experiment involved. More than one survey method (e.g., transect and tag recapture techniques) could be used in some studies to confirm abundance estimates as well as examining algal habitat changes.

### 4.5 Genetics and Disease Management

Genetic tools may be used in a variety of conservation efforts on abalone for: (1) enforcement purposes by identifying confiscated tissue samples to species, and identifying abalone samples illegally harvested from specific closed areas; (2) delineation of the geographic scale of independent populations of an abalone species and helping to define appropriate sizes of marine reserves; and (3) implementing genetic controls in hatcheries and monitoring hatchery reared seed releases to avoid inbreeding and loss of genetic diversity in wild stocks (Withler 2000). Human impacts have caused adverse genetic impacts on wild fish populations (Sheridan 1995). Blankenship and Leber (1995) advocated genetic monitoring prior to, during, and after stocking enhancement projects and the use of sufficient numbers of broodstock to minimise undesirable genetic effects of inbreeding. To reduce contamination of genetically separate stocks, hatchery reared progeny should be released in the same general area where their parent broodstock were collected. Protection of genetic diversity and possible genetic

improvement programmes in abalone aquaculture should be considered (Elliott 2000). Currently genetic analysis of northern abalone populations are underway.

Understanding the diseases that cause abalone mortality in the wild and in culture is of importance. Bower (2000) provides a review of abalone diseases and emphasises the need for guidelines and precautions to protect wild stock survival and to avoid curtailing aquaculture development by stopping the introduction of foreign pathogens while transplanting abalone. Rules, guidelines and transplant permits for health protection of marine invertebrates are administered through a government transplant committee.

Specific evaluation criteria for genetic and disease/health management of northern abalone rehabilitation is beyond the scope of this paper and should be dealt with in other documents.

## 5.0 DISCUSSION

There are a large number of short-term and long-term pilot experiments needed to help understand the factors that may help determine the combination of factors to be used in any large scale rehabilitation attempt. The results of the genetic analyses for estimating abalone population geographic discreteness will be important in deciding on the sizes of the experimental marine reserves and eventually mpas if they are deemed an appropriate tool for abalone rehabilitation.

The measurement of success of rehabilitation methods could be considered in a variety of ways which include: 1. Stopping further decline and increasing abalone populations by measuring density such as measured at survey index sites; 2. Increase abalone density in areas to a sustainable level for a prolonged (10 years) period, e.g., $\geq$ 50 % of 1970s abalone densities; 3. Being able to identify, through experimental results, the appropriate criteria that will provide successful recruitment and sustainability within abalone populations; 4. Clear indication that poaching has been controlled and stopped (see also Campbell 1997 for discussion).

Likelihood of success for larval seeding as a rebuilding tool is poor. Larval seeding is not recommended because survival rates are low, and post-larval habitat requirements are poorly known, no easy tag is available to help distinguish outplanted larvae from wild stock and no hatchery is near experimental sites under consideration.

The likelihood of success for seeding with hatchery-reared juveniles is uncertain. Conducting multiple replicate trials in several regions of B.C. will provide an estimate of the probability of success and directions for improving methods. Outplanting hatchery-reared juveniles to the wild can result in growth without active husbandry, but whether or not those juveniles will successfully reproduce and sustain a renewing population is unknown and should be investigated. Tagging outplanted abalone will be essential in monitoring growth and survival rates. Ensuring protection from poaching is essential for the long-term success of juvenile seeding. Genetic and disease monitoring and management will also be important.

The experimental marine reserves, combined with adult manipulations, will probably provide the most useful information on the biological and ecological requirements of northern abalone and the species rehabilitation.

## 6.0 RECOMMENDATIONS

1. Enforcement for the prevention of poaching northern abalone and partnerships between local communities and government agencies are imperative to the success of any rehabilitation attempts and long-term experiments.
2. Maintain northern abalone fishery closure indefinitely and continue large-scale index site surveys every 4-5 years to monitor long-term trends in northern abalone populations.
3. Establish experimental marine areas (closed to all dive fisheries) in (1) Queen Charlotte Islands, (2) central/north coast of B.C., (3) west coast of Vancouver Island, and (4) an area with sea otters present. Experimental manipulation of wild abalone adult densities should be attempted to increase abalone recruitment. Manipulation of red sea urchins abundance to determine the effects on abalone survival and growth is suggested in some of the treatment sites of the experimental marine areas.
4. Experimental outplanting of hatchery-reared northern abalone juveniles should be attempted, on a small scale, to determine optimal size and density for release and the probability of success in increasing juvenile and adult abalone densities.
5. An ecosystem approach is recommended in which habitat parameters, algal and invertebrates are monitored in all surveys and experiments.

## 7.0 ACKNOWLEDGEMENTS

We thank J. Harding for helping with literature collection and Norm Sloan and Mia Tegner for comments on this paper.

## 8.0 REFERENCES

Andrew, N. L., and A. J. Underwood. 1992. Associations and abundance of sea urchins and abalone on shallow subtidal reefs in southern New South Wales. Aust. J. Mar. Freshwater Res. 43: 1547-1559.

Andrew, N. L., D. G. Worthington, P. A. Brett, N. Bentley, R. C. Chick, and C. Blount. 1998. Interactions between the abalone fishery and sea urchins in New South Wales. New South Wales Fisheries Final Report Series No. 12, NSW Fisheries Research Institute, Cronulla.

Blankenship, H. L., and K. M. Leber. 1995. A responsible approach to marine stock enhancement. American Fisheries Society Symposium 15: 167-175.

Babcock, R., and J. Keesing. 1999. Fertilization biology of the abalone *Haliotis laevigata*: laboratory and field studies. Can. J. Fish. Aquat. Sci. 56: 1668-1678.

Bower, S. M. 2000. Infectious diseases of abalone (*Haliotis* spp.) and risks associated with transplantation. Can. Spec. Publ. Fish. Aquat. Sci. 130: 111-122.

Breen, P. A., and B. E. Adkins. 1980. Spawning in a British Columbia population of northern abalone, *Haliotis kamtschatkana*. Veliger 23: 177-179.

Breen, P. A., and B. E. Adkins. 1979. A survey of abalone populations on the east coast of the Queen Charlotte Islands, August 1978. Fish. Mar. Serv. Manuscr. Rep. 1490: 125p.

Burton, R. S., and M. J. Tegner. 2000. Enhancement of red abalone *Haliotis rufescens* stocks at San Miguel Island: reassessing a success story. Mar. Ecol. Prog. Ser. 202: 303-308.

Campbell, A. 1997. Possible criteria for reopening the northern abalone (*Haliotis kamtschatkana*) fishery in British Columbia. Can. Stock Assessment Secretariat Res. Doc. 97/64. 47 p.

Campbell, A. [editor] 2000a. Proceedings of the workshop on rebuilding abalone stocks in British Columbia. Can. Spec. Publ. Fish. Aquat. Sci. 130. xiv+158p.

Campbell, A. 2000b. Review of northern abalone, *Haliotis kamtschatkana*, stock status in British Columbia. Can. Spec. Publ. Fish. Aquat. Sci. 130: 41-50.

Clavier, J. 1992. Fecundity and optimal sperm density for fertilization in the ormer (*Haliotis tuberculata* L.). *In* Abalone of the world: biology, fisheries and culture. *Edited by* S. A. Shepherd, M. J. Tegner and S. A. Guzman del Proo. Fishing News Books, Blackwell Sci. Pub. Ltd., Oxford, U. K. pp. 86-92.

Cripps, K., and A. Campbell. 1998. Survey of abalone populations at Dallain Point and Higgins Pass, central coast of British Columbia, 1995 - 96. Can. Manuscr. Rep. Fish. Aquat. Sci. 2445: 31 p.

Davis, G.E. 1995. Recruitment of juvenile abalone (*Haliotis* spp.) measured in artificial habitats. Mar. Freshwat. Res. 46: 549-554.

Davis, E. G. 2000. Refugia-based strategies to restore and sustain depleted abalone populations in southern California. Can. Spec. Publ. Fish. Aquat. Sci. 130: 133-138.

Dugan, J. E., and G. E. Davis. 1993. Applications of marine refugia to coastal fisheries management. Can. J. Fish. Aquat. Sci. 50: 2029-2042.

Ebert, T. B. 1989. Growth of hatchery-reared red abalone at Fitzgerald marine reserve: One year post-release. Calif. Fish & Game 75(3): 178 – 179

Ebert, T. B., and E. E. Ebert. 1988. An innovative technique for seeding abalone and preliminary results of laboratory and field trials. Calif. Fish Game 74(2): 68 – 81.

Edgar, G. J., and N. S. Barrett. 1999. Effects of the declaration of marine reserves on Tasmanian reef fishes, invertebrates and plants. J. Exp. Mar. Biol. Ecol. 242: 107-144.

Elliott, N. G. 2000. Genetic improvement programmes in abalone: what is the future?. Aquaculture Res. 31: 51-59.

Emmett, B., and G. S. Jamieson. 1988. An experimental transplant of northern abalone, *Haliotis kamtschatkana*, in Barkley Sound, British Columbia. Fish. Bull. (U.S.) 87: 95-104.

Gaffney, P. M., V. P. Rubin, D. Hedgecock, D. A. Powers, G. Morris, and L. Hereford. 1996. Genetic effects of artificial propagation: signals from wild and hatchery populations of red abalone in California. Aquaculture 143: 257 – 266.

Garcia-Charton, J. A., and A. Perez-Ruzafa. 1999. Ecological heterogeneity and the evaluation of the effects of marine reserves. Fish. Res. 42: 1-20.

Gardner, J., J. Griggs, and A. Campbell. 2000. Summary of a strategy for rebuilding abalone stocks in British Columbia. Can. Spec. Publ. Fish. Aquat. Sci. 130: 151-155.

Hart, A. M., H. K. Gorfine, and M. P. Callan. 1997a. Abundance estimation of blacklip abalone (*Haliotis rubra*) I. An analysis of diver-survey methods used for large-scale monitoring. Fish. Res. 29: 159 - 169.

Hart, A. M., and H. K. Gorfine. 1997b. Abundance estimation of blacklip abalone (*Haliotis rubra*) I. A comparative evaluation of catch-effort, change-in-ratio, mark-recapture and diver-survey methods. Fish. Res. 29: 159 - 169.

Hilborn, R. 1998. The economic performance of marine stock enhancement projects. Bull. Mar. Sci. 62: 661-674.

Hirayama, N., S. Yamada, H. Kikuchi, and J. Yamada. 1989. A modification of DeLury method to abalone fishery. Nippon Suisan Gakkashi. 55: 409-416.

Inoue, M. 1976. Abalone. In Japan Fish. Coop. Assoc., Aquaculture Handbook. 1: 19 – 61.

Jamieson, G. S. 2000. Marine protected areas and their relevance to abalone conservation in British Columbia. Can. Spec. Publ. Fish. Aquat. Sci 130: 139-147.

Jamieson, G. S. and J. Lessard. 2000. Marine protected areas and fishery closures in British Columbia. Can. Spec. Publ. Fish. Aquat. Sci. 131. 414p.

Jamieson, G. S., and C. Levings. 2000. Marine protected areas in Canada – implications for both conservation and fisheries management. Can. J. Aquat. Fish. Sci. 58: 138-156.

Kiyomoto, S., and M. Yamasaki. 1997. Habitat of the 0-year-old *Haliotis discus discus* in south west Japan. Abstracts of the third international abalone symposium, Monterey, U.S.A. p. 84.

Mayfield S., L. Day, and G. Branch. 1997 The vital role of urchins and the influence of rock lobsters on juvenile abalone, *Haliotis midae*. Abstracts of the third international abalone symposium, Monterey, U.S.A. p. 47.

McCormick, T. B. 2000. Abalone (*Haliotis* spp.) aquaculture: present status and a stock enhancement tool. Can. Spec. Publ. Fish. Aquat. Sci. 130: 55–60.

McCormick, T. B., K. Herbinson, T. S. Mill, and J. Altick. 1994. A review of abalone seeding, possible significance and a new seeding device. Bull. Mar. Sci. 55: 680–693.

McShane, P. E. 1994. Estimating the abundance of abalone (*Haliotis* spp.) stocks - examples from Victoria and southern New Zealand. Fish. Res. 19: 379 - 394.

McShane, P. E. 1995a. Recruitment variation in abalone: its importance to fisheries management. Mar. Freshwater Res. 46: 555-570.

McShane, P. E. 1995b. Estimating the abundance of abalone: the importance of patch size. Mar. Freshwater Res. 46: 657-662.

Menge, B. A. 1997. Detection of direct versus indirect effects, were experiments long enough. Am. Nat. 149: 801-823.

Miyamoto, T., K. Saito, S. Motoya, and K. Kawamura. 1982. Experimental studies on the release of the cultured seeds of abalone, *Haliotis discus hannai* Ino in Oshoro Bay, Hokkaido. Sci. Repts. Hokkaido Fisheries Experimental Station, No. 24: 59 – 89. (english abstract, figures and tables).

Momma, H., K. Kobayashi, T. Kato, Y. Sasaki, T. Sakamoto, and H. Murata. 1980. [On the artificial propagation method of abalone and its effects on rocky shore. I. Remaining ratio of the artificial seed abalone (*Haliotis discus hannai* Ino) on lattice artificial reefs.] Suisan Zoshoku [The Aquaculture], 28(2): 59 – 65. Translation by M. Mottet, State of Washington, Department of Fisheries. From Tegner & Butler 1985.

Nash, W. J., T. L. Sellers, S. R. Talbot, A. J. Cawthorn, and W. B. Ford. 1994. The population biology of abalone (*Haliotis* species) in Tasmania. I. Blacklip abalone (*H. rubra*) from the north coast and islands of Bass Strait. Sea Fish. Div, Tasmania, Tech Rep. No. 48.

Ortiz-Quintanilla, M. 1980. Un sistema para inducir el desove de abulón en lost campos prequeros de Baja California, México. Memorias del segundo simposio latinoamericano de acuaculture. 1: 871 - 881.

Perry, R. I. 1999. Scientific concepts for ecosystem-based management of marine invertebrates in Canada's Pacific Coast. Can. Stock Assessment Secretariat Res. Doc. 99/123. DFO, 200 Kent Street, Ottawa, Ont. Canada K1A OE6.

Preece, P. A., S. A. Shepherd, S. M. Clark, and J. K. Keesing. 1997. Abalone stock enhancement by larval seeding: effect of larval density on settlement and survival. Moll. Res. 18: 265–273.

Quayle, D. B. 1971. Growth, morphometry and breeding in the British Columbia abalone, (*Haliotis kamtschatkana* Jonas). Fish. Res. Board Can. Tech. Rep. 279. 84 p.

Rudd, M. 1995. Abalone stock enhancement: a review of rationale and techniques. Bull. Aquacul. Assoc. Canada 95-4: 13–16.

Roberts, C. M. 1998. Sources, sinks, and the design of marine reserve networks. Fisheries 23: 16-19.

Roberts, R. D., T. Kawamura, and H. Takami. 1999. Abalone recruitment – an overview of some recent research in New Zealand, Australia and Japan. Bull. Tohoku Natl. Fish. Res. Inst. 62: 95-107.

Rogers-Bennett, L., and J. S. Pearse. 1998. Experimental seeding of hatchery-reared juvenile red abalone in northern California. J. Shellfish Res. 17: 877-880.

Rogers-Bennett, L., and J. S. Pearse. (in press) Indirect benefits of marine protected areas for juvenile abalone. Conservation Bio.

Rogers-Bennett , L., P. Haaker, and K. Karpov. 2000. Selecting and evaluating marine protected areas for abalone in California. (abstract) J. Shellfish Res. 19: 530-531.

Schiel, D. R. 1992. The enhancement of paua (*Haliotis iris* Martyn) populations in New Zealand. . *In* Abalone of the world: biology, fisheries and culture. *Edited by* S. A. Shepherd, M. J. Tegner and S. A. Guzman del Proo. Fishing News Books, Blackwell Sci. Pub. Ltd., Oxford, U. K. pp. 474–484.

Schiel, D. R. 1993. Experimental evaluation of commercial-scale enhancement of abalone *Haliotis iris* populations in New Zealand. Mar. Ecol. Prog. Ser. 97: 167-181.

Schiel, D. R., and B. C. Welden. 1987. Responses to predators of cultured and wild red abalone, *Haliotis rufescens*, in laboratory experiments. Aquaculture 60: 173 – 188.

Seki, T., and M. Sano. 1998. An ecological basis for the restoration of Japanese abalone populations. Bull. Tohoku Natl. Fish. Res. Inst. 60: 23-40.

Seki, T., and K. Taniguchi. 2000. Rehabilitation of northern Japanese abalone, *Haliotis discus hannai*, populations by transplanting juveniles. Can. Spec. Publ. Fish. Aquat. Sci. 130: 72-83.

Shepherd, S. A. 1985. Power and efficiency of a research diver, with a description of a rapid underwater measuring gauge: their use in measuring recruitment and density of an abalone population. *In* Diving for science 85. *Edited by* C. T. Mitchell Amer. Academy of underwater science. La Jolla, CA. pp. 263 - 272.

Shepherd, S. A., and P. A. Breen. 1992. Mortality in abalone: its estimation, variability and causes. *In* Abalone of the world: biology, fisheries and culture. *Edited by* S. A. Shepherd, M. J. Tegner and S. A. Guzman del Proo. Fishing News Books, Blackwell Sci. Pub. Ltd., Oxford, U. K. pp. 276-304.

Shepherd, S. A., and L. D. Brown. 1993. What is an abalone stock: implications for the role of refugia in conservation. Can. J. Fish. Aquat. Sci. 50: 2001-2009.

Shepherd, S. A., P. A. Preece, and R. W. G. White. 2000. Tired nature's sweet restorer? Ecology of abalone (*Haliotis* spp.) stock enhancement in Australia. Can. Spec. Publ. Fish. Aquat. Sci. 130: 84-97.

Sheridan, A. K. 1995. The genetic impacts of human activities on wild fish populations. Reviews Fish. Science 3: 91-108.

Sloan, N. A., and P. A. Breen. 1988. Northern abalone, *Haliotis kamtschatkana*, in British Columbia: fisheries and synopsis of life history information. Can Spec. Publ. Fish. Aquat. Sci. 103. 46 p.

Stoner, A. W., and R. A. Glazer. 1998. Variation in natural mortality: implications for stock enhancement. Bull. Mar. Sci. 62: 427-442.

Sweijd, N., Q. Snethlage, D. Harvey, and P. Cook. 1998. Experimental abalone (*Haliotis midae*) seeding in South Africa. J. Shellfish Res. 17: 897 – 904.

Tegner, M. J. 1992. Brood stock transplants as an approach to abalone stock enhancement. *In* Abalone of the World: Biology, Fisheries and Culture. *Edited by* S.A. Shepherd, M.J. Tegner, and S.A. Guzman del Proo. Fishing News Books, Oxford. pp. 461-473.

Tegner, M. J. 1993. Southern California abalones: Can stocks be rebuilt using marine harvest refugia? Can. J. Fish. Aquat. Sci. 50: 2010-2018.

Tegner, M. J. 2000. Abalone (*Haliotis* spp.) enhancement in California: what we've learned and where we go from here. Can. Spec. Publ. Fish. Aquat. Sci. 130: 61-71.

Tegner, M. J., and R. A. Butler. 1985. The survival and mortality of seeded and native red abalones, *Haliotis rufescens*, on the Palos Verdes Peninsula. Calif. Fish Game. 71: 150-163.

Tegner, M. J., and R. A. Butler. 1989. Abalone seeding. *In* Handbook of culture of abalone and other marine gastropods. *Edited by* K.O. Hahn. CRC Press, Inc.: Boca Raton, FL. pp. 157 – 182.

Tegner, M. J., and L. A. Levin. 1982. Do sea urchins and abalone compete in California kelp forest communities? *In* International Echinoderms Conference, Tampa Bay. *Edited by* J. M. Lawrence. pp 265-271.

Tong, L. J., G. A. Moss, and J. Illingworth. 1987. Enhancement of a natural population of the abalone, *Haliotis iris*, using cultured larvae. Aquaculture 62: 76–72.

Turner, N. J., M. Boelscher Ignace, and R. Ignace. 2000. Traditional ecological knowledge and wisdom of aboriginal peoples in British Columbia. Ecological Applications 10: 1275-1287.

Wallace, S. S. 1999. Evaluating three forms of marine reserves on Northern Abalone (*Haliotis kamtschatkana*) populations in British Columbia, Canada. Conservation Biol. 13: 882-887.

Watson, J. C. 2000. The effects of sea otters (*Enhydra lutris*) on abalone (*Haliotis* spp.) populations. Can. Spec. Publ. Fish. Aquat. Sci. 130. 123-132.

Withler, R. E. 2000. Genetic tools for identification and conservation of exploited abalone (*Haliotis* spp.) species. Can. Spec. Publ. Fish. Aquat. Sci. 130: 101-110.

Underwood, A. J. 1997. Experiments in ecology. Cambridge University Press, Cambridge.

Table 1. Summary of advantages and requirements of some potential methods to rebuild northern abalone population in B. C.

| Possible Methods | Stocking Hatchery-reared Larvae Seed | Stocking Hatchery-reared Juvenile Seed | Experimental Marine Areas Wild Stock Manipulations | Marine Protected Areas | Fishery Closure and Enforcement |
|---|---|---|---|---|---|
| **Likelihood of success** | poor | uncertain | fair to good | fair to good | fair to good |
| **Advantages** | ▪ relative low cost<br>▪ larvae available<br>▪ minimal hatchery facilities required<br>▪ juvenile behaviour developed in wild<br>▪ published trials | ▪ juveniles available at moderate cost<br>▪ no active culturing required after seeding<br>▪ published trials show promise | ▪ uses local wild stocks<br>▪ no risk of transplanting disease<br>▪ published trials show promise | ▪ advantageous to other species<br>▪ involves other stakeholders<br>▪ allows natural rebuilding | ▪ increases public awareness<br>▪ encourages local stewardship<br>▪ allows natural rebuilding<br>▪ some steps already in progress |
| **Disadvantages** | ▪ high mortality<br>▪ difficult to monitor<br>▪ difficult to distinguish hatchery-reared seed<br>▪ restricted by larval stock availability | ▪ time consuming to monitor<br>▪ may have high mortality due to behavioural deficiencies<br>▪ restricted by juvenile stock availability | ▪ complex to monitor<br>▪ risk of poaching curtailing experiment | ▪ difficult to enact &enforce<br>▪ requires co-operation of other agencies for implementation and maintenance<br>▪ long-term effects unknown<br>▪ size and number required unknown | ▪ expensive<br>▪ difficult to enforce<br>▪ relies on other agencies and community groups for implementation |
| **Requirements** | ▪ local larvae; i.e. aquaculture products<br>▪ practical way to monitor larval survival short and long term | ▪ local juveniles; i.e. aquaculture products<br>▪ practical way to monitor juvenile survival short and long term | ▪ local wild stocks of mature adults<br>▪ practical way to monitor adult contribution to reproductive output and recruitment | ▪ healthy local wild stocks<br>▪ adequate enforcement | ▪ C & P participation<br>▪ DNA database<br>▪ First Nations guardians assistance<br>▪ public education |
| **Site Selection Criteria** | ▪ suitable habitat for larval settlement<br>▪ adequate food source<br>▪ hatchery near site<br>▪ reasonable access in most weather year round<br>▪ easy to close to other fishing activity<br>▪ barriers to immigration or emigration | ▪ suitable habitat for juveniles<br>▪ adequate food source<br>▪ reasonable access in most weather year round<br>▪ easy to close to other fishing activity<br>▪ barriers to immigration or emigration | ▪ reasonable access in most weather year round<br>▪ easy to close to other fishing activity<br>▪ barriers to immigration/emigration | ▪ healthy local wild stocks<br>▪ adequate food sources<br>▪ easy to close to other fishing activity<br>▪ information on abalone biology & ecology to determine size and number of mpas required | ▪ Survey past abalone index sites |
| **Survey data to collect are** | ▪ substrate<br>▪ slope | ▪ depth<br>▪ temperature | ▪ abalone abundance<br>▪ urchin abundance | | ▪ continue index site surveys |

| | | | | | |
|---|---|---|---|---|---|
| **common to all experiments:** | • exposure<br>• current<br>• natural barriers | • salinity<br>• visibility | • abalone size frequencies<br>• sea stars abundance<br>• algae species abundance | | throughout B.C. |

Table 2. Approximate time schedules for research on rebuilding methods and surveys of northern abalone in B.C.

| Methods | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| **General Area Selections** | | | | | | | | | | |
| Initial Habitat - Surveys | — | | | | | | | | | |
| - Report | | — | | | | | | | | |
| **Expt. Marine Reserve area** | | | | | | | | | | |
| Site selection, mapping, marking | | — | | | | | | | | |
| Stock & Habitat surveys | | — | — | — | — | — | — | — | — | — |
| Abalone Manipulation | | | — | — | | | | | | |
| Red Sea Urchin Manipulation | | | — | | | | | | | |
| Reports | | | | – | | – | | | – | |
| **Juvenile seed Stocking** | | | | | | | | | | |
| Aquaculture production | | — | | | | | | | | |
| Site selection, mapping, marking | | — | | | | | | | | |
| Stock & Habitat surveys | | — | — | — | — | — | — | — | — | — |
| Outplanting juvenile seed | | | — | — | | | | | | |
| Reports | | | | — | — | | | — | | |
| **Fishery Closure - Monitoring** | | | | | | | | | | |
| Index site surveys - Central Coast | — | | | | | — | | | — | |
| - QCI | | — | | | | | — | | | — |
| Reports (a year after each survey) | | – | — | | | – | – | | | – – |
| **Subsidiary Methods Testing** | | | | | | | | | | |
| Juvenile transplanting | | — | | | | | | | | |
| Survey methods | — | | | | | | | | | |
| Larval collectors | | — | | | | | | | | |
| Juvenile collectors | | — | | | | | | | | |
| Tagging | | — | | | | | | | | |
| Reports | | | — | — | | | | | | |

Table 3. Example of an experimental design showing the treatments of stocking abalone juvenile seed at two release sizes (S1, S2), two densities (D1, D2), and including red sea urchins (U) and no urchins (NU) (through removal). Not adding abalone seed to sites will be considered as controls without modules (C1) and with modules but no seed (C2, procedural control).

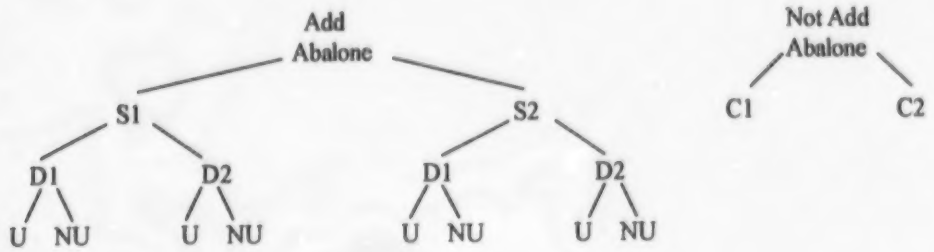


Table 4. Example of an experimental design testing the removal and addition of adult abalone in sites with red sea urchins (U) or no urchins (NU).